JC14 Rec'd PCT/PTO 14 DEC 2001

Customized FORM PTO-1390 U S DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE		ATTORNEY DOCKET NO. P07446US00/RFH
TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371		U.S. APPLICATION NO 10/018054
INTERNATIONAL APPLICATION NO. PCT/AU00/00698	INTERNATIONAL FILING DATE 21 JUNE 2000	PRIORITY DATE CLAIMED 21 JUNE 1999
TITLE OF INVENTION: METHOD OF FORMING AN OPTICAL WAVEGUIDE DEVICE		
APPLICANT(S) FOR DO/EO/US: CHARTERS, Robert B. et al.		

Applicant herewith submits to the US Designated/Elected Office (DO/EO/US) the following items and other information:

- ☒ 1. This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
- ☐ 2. This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 USC 371.
- ☒ 3. This express request to begin national examination procedures (35 USC 371(f)) at any time rather than delay examination until the expiration of the applicable time limit set in 35 USC 371(b) and PCT Art. 22 and 39(1).
- ☒ 4. A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.
- ☒ 5. A **copy** of the International Application as filed (35 U.S.C. 371 (c)(2))
  - ☐ a. is transmitted herewith (required only if not transmitted by the International Bureau).
  - ☒ b. has been transmitted by the International Bureau.
  - ☐ c. is not required, as the application was filed in the United States Receiving Office (RO/US).
- ☐ 6. A **translation** of the International Application into English (35 U.S.C. 371(c)(2)).
- ☒ 7. Amendments to the claims of the International Appln. under PCT Article 19 (35 USC 371 (c)(3))
  - ☐ a. are transmitted herewith (required only if not transmitted by the International Bureau).
  - ☐ b. have been transmitted by the International Bureau.
  - ☐ c. have not been made; however, the time limit for making such amendments had NOT expired.
  - ☒ d. have not been made and will not be made.
- ☐ 8. A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
- ☐ 9. An **oath** or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).
- ☐ 10. A translation of the annexes to the Int'l Prelim. Exam. Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11. to 20. below concern document(s) or information included:

- ☐ 11. An **Information Disclosure Statement** under 37 C.F.R. 1.97 and 1.98.
- ☐ 12. An **Assignment** document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3 31 is included
- ☒ 13. A **First preliminary amendment.**
- ☐ 14. A Second or Subsequent preliminary amendment.
- ☐ 15. A substitute specification.
- ☐ 16. A change of power of attorney and/or address letter.
- ☐ 17. A computer-readable form of the sequence listing in accordance with PCT Rule 13ter.2 & 35 USC 1.821-825.
- ☐ 18. A second copy of the published international application under 35 USC 154(d)(4).
- ☐ 19. A second copy of the English translation of the international application under 35 USC 154(d)(4).
- ☐ 20. Other items or information:
  - ☐
  - ☐

☐ A copy of the Notification of Missing Requirements under 35 U.S.C. 371.

☐ In the event that a petition for extension of time is required to be submitted herewith, and in the event that a separate petition does not accompany this response, applicant hereby petitions under 37 CFR 1.136(a) for an extension of time of as many months as are required to render this submission timely. Any fee is authorized in 17(c).

Date: 14 December 2001

JC05 Rec'd PCT/PTO 14 NOV 2001

U.S. APPLICATION NO. *(If known)*	INTERNATIONAL APPLICATION NO.	ATTORNEY DOCKET NO.
10/018054	PCT/AU00/00698	P07446US00/RFH

☒ 21. **The following fees are submitted:**

☒ **Basic National Fee** (37 CFR 1.492 (a) (1)-(5):

			CALCULATIONS	*PTO USE ONLY*
☒	Neither Int'l Prelim. Exam. fee nor Int'l Search fee paid to USPTO	$1040		
☐	Search Report has been prepared by the EPO or JPO	$ 890		
☐	No Int'l Prelim. Ex. fee paid to USPTO but Int'l Search fee paid to USPTO	$ 740		
☐	International preliminary examination fee paid to USPTPO	$ 710		
☐	Int'l Prelim. Ex. fee paid to USPTO & all claims satisfied PCT Art. 33(1)-(4)	$ 100		

ENTER APPROPRIATE BASIC FEE AMOUNT =				$ 1040	
☐ Surcharge of **$130** for furnishing the oath or declaration later than from the earliest claimed priority date (37 CFR 1.492(e)).			☐ 20 mos. ☐ 30 mos. +	$	
CLAIMS	*NUMBER FILED*	*NUMBER EXTRA*	*RATE*		
Total Claims	7 - 20 =		X **$18** =	$	
Independent Claims	1 - 03 =		X **$84** =	$	
☐ Multiple Dependent Claim(s) (if applicable)			+ **$280** =	$	
TOTAL OF ABOVE CALCULATIONS =				$ 1040	
☒ Applicant claims small entity status. See 37 CFR 1.27. The fees indicated above are reduced by ½.			-	$ 520	
SUBTOTAL =				$ 520	
☐ Processing fee of **$130** for furnishing the **English translation** later than from the earliest claimed priority date (37 CFR 1.492(f)).			☐ 20 mos. ☐ 30 mos. +	$	
TOTAL NATIONAL FEE =				$ 520	
☐ Fee for recording the enclosed **assignment** (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). **$40** per property			+	$	
TOTAL FEES ENCLOSED =				$ 520	
Amount to be				*Refunded*	*$*
				Charged	*$*

☒ a. A **check** in the amount of $ 520 to cover the above fees is enclosed.

☐ b. Please charge my Deposit Account No. 12-0555 in the amount of $ to cover the above fees.

☒ c. The Commissioner is hereby authorized to charge any additional fees required or credit overpayment to Deposit Account No. 12-0555.

Note: *Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.*

SEND ALL CORRESPONDENCE TO:

ROSS F. HUNT, JR.

At the address (below) of **CUSTOMER NO. 00881.**

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SIGNATURE: Douglas E. Jackson

NAME: Douglas E. Jackson

REG. NO.: 28518

PHONE NO.: 703-739-4900

Date: 14 December 2001

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Patent

In re patent application of: CHARTERS et al.

Serial No.: NEW APPLICATION

Filed: On even date herewith

For: METHOD OF FORMING AN OPTICAL WAVEGUIDE DEVICE

Examiner:

Art Unit:

Dckt No.: P07446US00/RFH

PRELIMINARY AMENDMENT

Assistant Commissioner for Patents
Washington, D.C.

S I R:

Prior to examination, please amend the above-identified application as follows.

IN THE CLAIMS:

A clean version of the amended claims is provided herewith in **Attachment A**. It will be noted that the amended claims have been amended relative to the previously provided version as shown by the marked up version thereof in **Attachment B** provided herewith.

REMARKS

By this Amendment, the claims have been rewritten to reduce the multiple dependencies.

Further and favorable action is solicited.

Respectfully submitted,

Date: 12/14/01

By: Douglas E. Jackson
Douglas E. Jackson
Registration No. 28518

LARSON & TAYLOR PLC - 1199 North Fairfax Street, Suite 900 - Alexandria, Virginia 22314 -

ATTACHMENT A

Clean Replacement/New Claims (entire set of pending claims)

Following herewith is a clean copy of the entire set of pending claims.

1. A method of forming a digital directional coupler, which comprises at least two optical waveguides, said method comprising scanning a laser beam across a photosensitive material to induce refractive index changes in the material to form each of the waveguides, wherein the scanning speed is varied to create a refractive index taper of a selected functional form in each of the waveguides.

2. A method as claimed in claim 1 wherein the laser beam has a doughnut type irradiance distribution.

3. (amended) A method as claimed in claim 1 wherein the laser is a TEM_{01}* mode laser.

4. (amended) A method as claimed in claim 1 wherein the mode of the laser is chosen so as to provide an increased coupling strength between adjacent ones of the waveguides.

5. (amended) A method as claimed in claim 1 wherein the photosensitive material is in a planar form.

6. (amended) A method as claimed in claim 1 wherein the scanning speed is varied during the forming of each waveguide in a manner such that adjacent ones of the waveguides are refractive index tapered in opposite directions.

7. (amended) An optical waveguide device when produced utilizing the method as claimed in claim 1.

ATTACHMENT B

Marked Up Replacement Claims

Following herewith is a marked up copy of each rewritten claim together with all other pending claims.

1. A method of forming a digital directional coupler, which comprises at least two optical waveguides, said method comprising scanning a laser beam across a photosensitive material to induce refractive index changes in the material to form each of the waveguides, wherein the scanning speed is varied to create a refractive index taper of a selected functional form in each of the waveguides.

2. A method as claimed in claim 1 wherein the laser beam has a doughnut type irradiance distribution.

3. (amended) A method as claimed in ~~any previous claim~~ claim 1 wherein the laser is a TEM_{01}* mode laser.

4. (amended) A method as claimed in ~~any previous claim~~ claim 1 wherein the mode of the laser is chosen so as to provide an increased coupling strength between adjacent ones of the waveguides.

5. (amended) A method as claimed in ~~any previous claim~~ claim 1 wherein the photosensitive material is in a planar form.

6. (amended) A method as claimed in ~~any previous claim~~ claim 1 wherein the scanning speed is varied during the forming of each waveguide in a manner such that adjacent ones of the waveguides are refractive index tapered in opposite directions.

7. (amended) ~~A digital directional coupler~~ An optical waveguide device when produced utilizing the method ~~of any one of the previous claims~~as claimed claim 1.

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Method of Forming an Optical Waveguide Device

Field of the Invention

The present invention relates to the field of formation of optical waveguide devices utilizing laser processing including e.g. the formation of digital directional couplers.

Background of the Invention

As telecommunications operators rapidly expand their existing fibre optic networks driven by the ever increasing demand for bandwidth, optical space switching is becoming an important function in all-optical networks. In particular, the adoption of optical space switches enables network reconfiguration and restoration (fault protection) at the optical level, rather than converting the optical signals to electronic form for switching purposes. The architecture of choice for switching devices is the planar lightwave circuit (PLC) since it allows many switching elements to be concatenated logically together to form a switching matrix on a single compact optical "chip".

As shown in Fig. 1, the basis of most PLC's is a trilayer of optically transparent thin films deposited on a substrate of generally silicon or silica 1. The central, or core layer 2 of the sandwich structure normally has higher refractive index than the outer cladding layers 3,4, and this simple system is known as a planar waveguide. Light injected into the core layer 2 undergoes total internal reflection at both core/cladding boundaries and is confined in this transverse dimension, resulting in 1-dimensional light guidance. However as a consequence of the constant refractive index in the plane of the film total internal reflection is not possible, and light spreads or diffracts laterally in the guiding layer. To impart useful functionality to a planar waveguide, 2-dimensional light guidance is required, and planar diffraction must be overcome by locally increasing the refractive index in the core layer. The light guides so formed are known as channel waveguides, the basic elements of optical space switches.

One of the simplest forms of optical space switch is the directional coupler which is illustrated schematically in Fig. 2. In this four port device 10, two identical single mode channel waveguides 11,12 are brought into close proximity with one another such that the electric field of one guided mode overlaps with the high refractive index guiding region of the other waveguide. With light injected into port 1, a resonant interaction results in an oscillatory power transfer between the two waveguides with device length. This occurs since the guides are identical and the lightwaves in the individual waveguides propagate through the structure at the same velocity. Under these conditions the guides are said to be phase matched and 100% power may be transferred between guides. Judicious choice of the length of the interaction region allows any fraction of optical power to be split between the output waveguides, ports 3 and 4. For switching applications, the interaction length is often chosen such that all the power entering port 1 exits at port 3; the device is said to be in the 'cross' state.

Switching can then be achieved by modifying the refractive index of one or both of the waveguide core regions such that propagation of light waves through the individual guides of the structure occurs at different velocities. The waveguides are then phase mismatched, the interaction between the guides is no longer resonant and the power transfer effect is diminished such that light injected into port 1 now exits through port 4. The device is then said to be in the "bar" state. In practice, detuning of the device may be achieved by the thermo-optic effect (polymer, sol-gel and silica PLC's), the electro-optic effect (ferroelectric waveguides) or carrier injection (semiconductor waveguides). For low speed (~1msec) switching applications the thermo-optic mechanism is more favorable since the effect is independent of polarization, allowing all input light polarization states to be switched by the same amount. A typical switching response of a directional coupler operating under this

regime is shown in Fig. 3, where the crosstalk, X, is defined as;

$$X = 10Log_{10}\left(\frac{P_3}{P_3 + P_4}\right) \qquad (1)$$

and P_i is the optical power at port i.

It can be seen that the switching process is efficient but sidelobes in the device response are always present. To maintain a low crosstalk value in the switched state therefore requires that operation occur in a narrow region e.g. 20 between sidelobes, placing severe constraints on the associated control system electronics. A reduction in sidelobe level can be obtained through the use of distributed coupling, in which instead of the two waveguides running parallel to one another, their separation is tapered in a specific continuous manner reaching a minimum at the centre of the device. This procedure can minimize sidelobe level but still requires operation in a sidelobe minimum to achieve sufficiently low crosstalk. A digital switching response exhibiting no sidelobes would therefore be advantageous.

An alternative but equivalent view of the coupling process is obtained by considering the compound two-waveguide structure. In this model coupling is described by the interference of the normal modes of the compound structure which maintain their shape along the device length but travel at different velocities. A cross state is obtained when the device length is such that the supermodes have a relative phase difference of π or odd multiples thereof, interfering constructively at port 3 and destructively at port 4. The presence of sidelobes in the switching response may then be attributed to further interference effects as the device is detuned.

The major disadvantage of directional couplers for optical switching applications is that although very low crosstalk values (<-40dB) are theoretically possible, to achieve this performance in a real world device requires

that a supermode phase difference of π must be accurately and repeatably attained for the unswitched state. Small fluctuations in the core refractive index or device length accrued in the manufacturing process, and the additional requirement of diverging the waveguides to a 250μm separation to interface with optical fibres, currently renders -40dB crosstalk values in this class of switching device an elusive goal. In addition, the emergence of wavelength division multiplexing (WDM) as the accepted method of expanding the bandwidth of existing optical networks introduces the requirement that the response of optical space switches be independent of wavelength over a range of typically 40nm. Clearly since directional couplers operate through wavelength dependent interference effects, the low crosstalk criterion cannot be met for all wavelengths simultaneously and this class of device is unsuitable for these applications. Alternative device structures exhibiting wavelength independent, digital switching responses and low crosstalk are therefore sought.

A digital directional coupler (DDC) device that potentially satisfies the above requirements has been proposed and analyzed theoretically, (R. R. A. Syms and R. G. Peall, 'The digital optical switch: analogous directional coupler devices', *Optics Communications*, Vol. 69, No. 3,4, pp. 235-238, 1989, R. R. A. Syms, 'The digital directional coupler: improved design', *IEEE Photonics Technology Letters*, Vol. 4, No. 10, pp. 1135-1138, 1992. A schematic of the device is shown in Fig. 4a. This four port device comprises a distributed coupling directional coupler in which each waveguide is tapered in effective index, N_{ef}, in opposite directions, with a graph of the tapering being illustrated in Fig. 4b. The effective index will be proportional to waveguide width and/or core refractive index. In the unswitched state, the waveguides are identical and therefore phase matched in the centre of the device where their separation is a minimum and the interaction or coupling strength, $\kappa(0)$, is maximized. Significant power transfer between the waveguides therefore

takes place in this region to produce a device in the cross state. Detuning the device in a similar manner to standard directional coupler switches moves the phase matching position away from the device centre to regions of increased waveguide separation and consequently reduced coupling strength, $\kappa(z)$. Power transfer is therefore inhibited and the device is placed in the switched bar state. The key difference between this type of optical switch and a standard directional coupler is that operation is based on the 'slow changing of shape' or adiabatic evolution of a single 'supermode', induced by the gradual effective index changes along the device. Since only one 'supermode' is excited in the compound system, interference effects do not occur and the device shows the required properties of wavelength independent, digital switching. To maintain power in only one 'supermode' along the device and achieve adiabatic operation requires that the difference in effective indices of the two 'supermodes', ΔN_{ef}, supported by the compound system be maximized throughout the interaction length. Under this condition a difference in shape between 'supermodes' is maintained and the following constraints on device design may be derived;

$$\kappa(z) = \kappa(0)\sin\theta \qquad (2)$$

$$\Delta N_{ef} = \left(\frac{\lambda}{2\pi}\right)\kappa(0)\cos\theta \qquad (3)$$

where λ is the wavelength of light and θ is an S-shaped rotation function of typical form;

$$\theta = \left(\frac{\pi z}{L}\right) - 0.5\sin\left(\frac{2\pi z}{L}\right) \qquad (4)$$

for an interaction length, L. From equation (3) it is therefore clear that adiabatic operation will be best

obtained with strongly coupled waveguides (large $\kappa(0)$), requiring a small central waveguide separation.

Summary of the Invention

In accordance with a first aspect of the present invention, there is provided a method of forming a digital directional coupler, which comprises at least two optical waveguides, said method comprising scanning a laser beam across a photosensitive material to induce refractive index changes in the material to form each of the waveguides, wherein the scanning speed is varied to create a refractive index taper of a selected functional form in each of the waveguides.

The laser beam preferably can include a doughnut type irradiance distribution such as a $TEM_{01}*$ mode laser beam.

The laser can be utilized to produce a series of refractive index tapers in the waveguide of specified functional form. In one example, the mode of the laser can be chosen so as to provide an increased coupling strength of evanescently coupled waveguide devices constructed in accordance with the method. The method can be further utilised to reduce the optical cross coupling between connecting waveguides in an optical switching matrix. The method can also be utilised to form multiple optical switches on a single planar wafer. The method can also be utilised to produce substantially continuous refractive index taper profiles in laser written channel waveguides.

In accordance with a second aspect of the present invention, there is provided an optical waveguide device when produced utilising the method of the first aspect of the present invention.

Brief Description of the Drawings

Notwithstanding any other forms which may fall within the scope of the present invention, preferred forms of the

invention will now be described by way of example only, with reference to the accompanying drawings in which:

Fig. 1 illustrates a sectional schematic view of a planar waveguide;

Fig. 2 illustrates a schematic of a channel waveguide directional coupler;

Fig. 3 illustrates a graph of the typical response of a directional coupler;

Fig. 4a illustrates a schematic of a typical digital directional coupler;

Fig. 4b illustrates the effective index for the arrangement of Fig. 4a;

Fig. 5 illustrates an example effective index and maximum core refractive index of a TEM_{01}* written waveguide, as a function of writing velocity;

Fig. 6 illustrates a comparison of coupling strengths for a TEM_{01}* and TEM_{00} laser beam; and

Fig. 7 illustrates a simple schematic of the writing process of the preferred embodiment.

Description of Preferred and Other Embodiments

In practical terms, the fabrication of optical waveguide devices such as digital directional couplers is problematic using standard processes. In the microelectronics industry, the construction of complex waveguide structures normally utilizes a standard patterning technique known as mask photolithography. The first step in this process is to deposit an additional thin film of photoresist onto the planar waveguide core, usually by spin coating. The photoresist film is then preferentially exposed to a broadband extended UV source through an amplitude mask such that a photochemical reaction is initiated below the high transmission areas of the mask and the mask pattern (or its inverse) transferred to the photoresist layer. The pattern may then be defined in the waveguide core layer by removing core material from the unwanted regions by a process such as reactive ion etching (RIE). Removal of the remaining resist and

overcladding with a low refractive index film completes the standard processing of the PLC.

In the preferred embodiment, a more direct approach may be taken utilizing materials such as plastics, ormosils and some glasses that allow refractive index patterning to be achieved without the use of an additional photoresist layer. In this class of materials, direct exposure generally to UV radiation initiates a photochemical reaction that raises the refractive index of the core material, enabling channel waveguides to be formed. The materials are generically described as photosensitive, and, as will be demonstrated, enable DDC devices to be accurately defined using a new fabrication method.

The requirement for strongly coupled waveguides in digital directional couplers means that fabrication methods involving material removal such as RIE are not ideal as it is difficult to define individual waveguides in the central region of the structure with sufficient accuracy. In addition, since an extended UV source is used in both these photolithographic techniques the exposure is uniform across the whole wafer, and hence an induced refractive index change cannot vary from one part of the waveguide structure to the next. Tapers in guide effective index must therefore be obtained through tapers in waveguide width which places severe tolerances on the production of a suitable mask. Photolithographic masks are usually produced by electron beam writing systems which approximate continuously varying structures with constant segments offset by a step size of typically 50-100nm. Although small, these 'hard', discontinuous steps impact detrimentally on the minimum crosstalk value that can be obtained in waveguide devices. In addition, since the total change in guide width required to obtain a suitable change in effective index is small (≤1μm) in comparison with the interaction length (10-20mm), accurate control over the rotation function, θ, is not possible. To date mask-based photolithographic methods combined with RIE have

not produced mode evolution coupler type devices with acceptable optical performance.

In the preferred embodiment, an alternative fabrication process is used in which refractive index tapers are the primary method for producing the device. Importantly this method utilises a laser direct writing (LDW) technique. In contrast to standard mask photolithography, in the LDW process a photosensitive planar waveguiding film is accurately traversed under a focused laser beam to locally increase the refractive index and directly delineate the channel waveguides without the use of a mask. For constant laser power, the exposure and therefore the refractive index of the photosensitive material is typically related to the writing velocity. For example, Fig. 5 illustrates, for an example photosensitive material, the effective index and maximum core refractive index of a written waveguide as a function of writing velocity. Clearly by controlling the writing velocity, the refractive index of the waveguide core and therefore the waveguide effective index can be continuously varied along the device length. Furthermore, since the generated pattern is under direct software control, rotation functions of complex mathematical form may be experimentally produced. In comparison with mask technologies, although segmentation is still present, the use of spline tracking curves in both position and velocity results in 'soft' steps which do not affect crosstalk to a large degree, enabling values of <-40dB to be achieved. Therefore, the refractive index tapering achieved via LDW becomes a practical way of implementing mode evolution type device design.

It has been found that as a result of the scanning process using a laser writing with a Gaussian (TEM_{00}) laser beam the waveguide produced has a laterally graded refractive index profile. The use of a 'doughnut' (TEM_{01}*) laser beam produces waveguides with a more step-like refractive index distribution. Fig. 6 illustrates a comparison of the coupling strengths for the two different

type of laser beams. It can be seen that the $TEM_{01}*$ laser beam produces a larger value (typically by a factor of 1.6) of coupling strength, $\kappa(0)$, for the same waveguide separation and maximum exposure. With reference to equation (3) this is clearly beneficial for DDC devices.

Fig. 7 provides a simplified schematic view of the processing arrangement of the preferred embodiment in that a wafer 30 having a photosensitive core layer 31 is processed utilising a UV laser 32 utilizing a spatial translation system (not shown) under software control with a particular velocity and displacement profile so as to trace out a requisite path e.g. 33 in the photosensitive layer 31 so as to modify the refractive index in this traced out path.

In general for optical space switching applications, 2x2 switches are insufficient and multiport *NxN* devices are highly desired. It is usual to achieve this through waveguide connection of single 2x2 switching elements into a logical matrix, such that light input at any port can be redirected to any other unused output port independent of (strictly nonblocking) or dependent upon (blocking or re-arrangable nonblocking) the routing connection used. Since the interface to single mode optical fibres need only take place at the input and output waveguides, the requirement to separate the channel waveguides to a 250µm pitch only occurs in these areas of the optical 'chip'. Within the switching matrix itself the connecting waveguides need only be sufficiently separated to inhibit any cross coupling between nearest neighbour guides. In this respect laser written mode evolution type switches also offer advantages over existing methods. For instance, in a switching array constructed from 2x2 directional coupler switching nodes and mask type processing, the connecting waveguides must be the same width to efficiently interface with the input/output waveguides of the directional coupler. The connecting waveguides are therefore phase matched, and the switch matrix design is limited by the need to separate the waveguides to minimize resonant optical power transfer

between them. In the laser direct written DDC case the base device is inherently asymmetric and therefore the input/output waveguides are automatically phase mismatched. Power transfer between connecting waveguides is therefore suppressed independent of their spacing allowing more freedom in the design of the matrix. In particular, the density of connection waveguides per unit area of optical chip may be increased, reducing the overall dimensions of optical space switch matrices.

It would be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiment without departing from the spirit or scope of the invention as broadly described. The present embodiment is, therefore, to be considered in all respects to be illustrative and not restrictive.

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Received 7 September 2001

We Claim:

1. A method of forming a digital directional coupler, which comprises at least two optical waveguides, said method comprising scanning a laser beam across a photosensitive material to induce refractive index changes in the material to form each of the waveguides, wherein the scanning speed is varied to create a refractive index taper of a selected functional form in each of the waveguides.

2. A method as claimed in claim 1 wherein the laser beam has a doughnut type irradiance distribution.

3. A method as claimed in any previous claim wherein the laser is a $TEM_{01}*$ mode laser.

4. A method as claimed in any previous claim wherein the mode of the laser is chosen so as to provide an increased coupling strength between adjacent ones of the waveguides.

5. A method as claimed in any previous claim wherein the photosensitive material is in a planar form.

6. A method as claimed in any previous claim wherein the scanning speed is varied during the forming of each waveguide in a manner such that adjacent ones of the waveguides are refractive index tapered in opposite directions.

7. A digital directional coupler device when produced utilizing the method of any one of the previous claims.

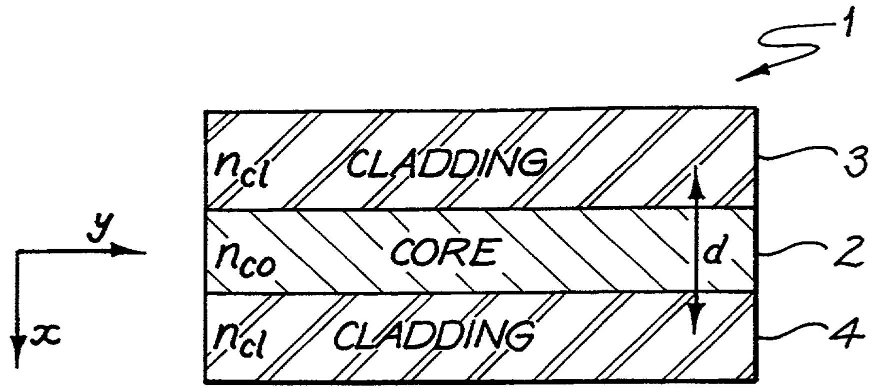
1
n_{cl} CLADDING
3
y
n_{co} CORE
d
2
x
n_{cl} CLADDING
4

FIG. 1

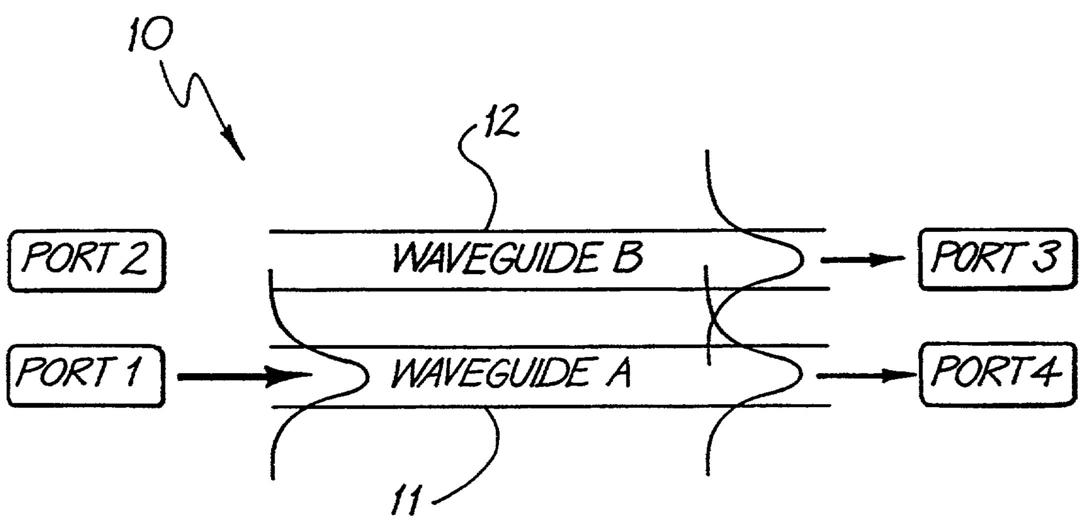
10
12
PORT 2
WAVEGUIDE B
PORT 3
PORT 1
WAVEGUIDE A
PORT4
11

FIG. 2

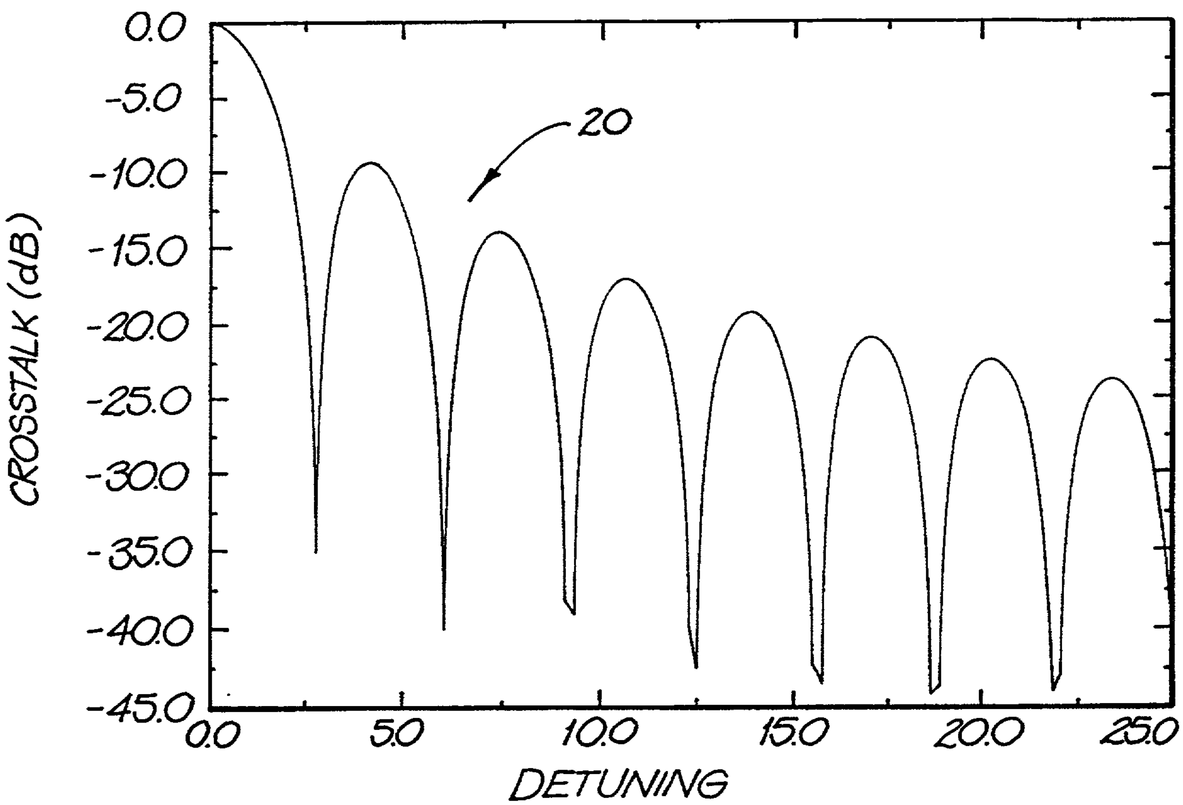
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
-30.0
-35.0
-40.0
-45.0
CROSSTALK (dB)
20
0.0
5.0
10.0
15.0
20.0
25.0
DETUNING

FIG. 3

SCHEMATIC & EFFECTIVE INDEX TAPERS OF A TYPICAL DIGITAL DIRECTIONAL COUPLER IN THE CROSS (SOLID) & BAR (DASHED) STATES.

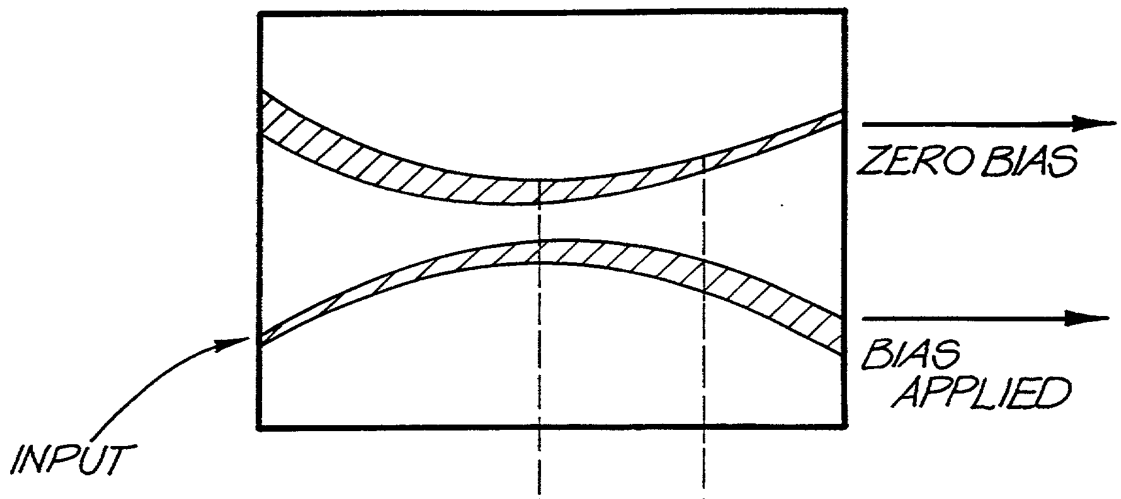

FIG. 4a

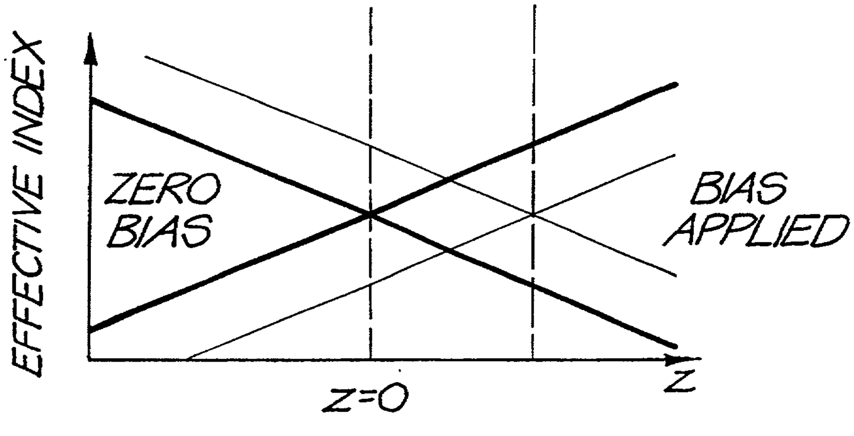

FIG. 4b

EFFECTIVE INDEX (SOLID) & MAXIMUM CORE REFRACTIVE INDEX (DASHED) OF A TEM_{01}* LASER WRITTEN WAVEGUIDE AS A FUNCTION OF WRITING VELOCITY.

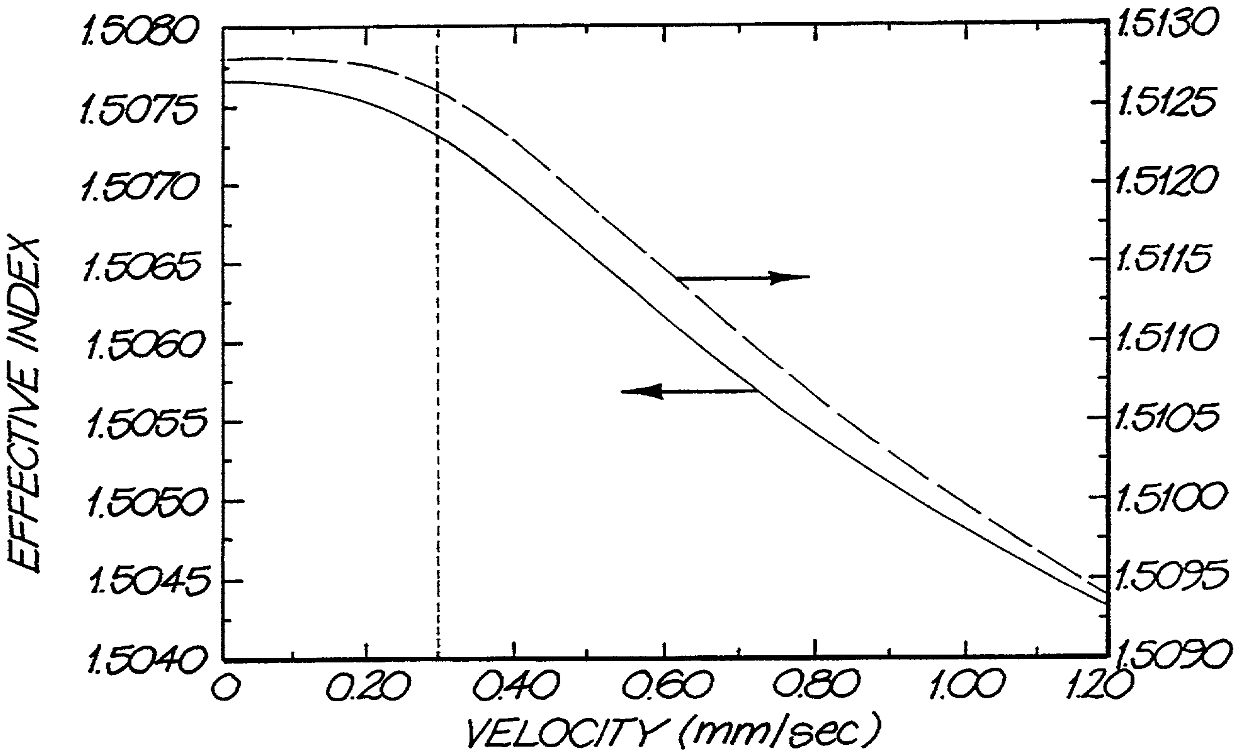

FIG. 5

COMPARISON OF COUPLING STRENGTHS, κ(O), FOR TEM_{01}* (SOLID) & TEM_{00} (DASHED) LASER WRITTEN DIRECTIONAL COUPLERS WITH EQUAL WAVEGUIDE SEPARATION & EXPOSURE.

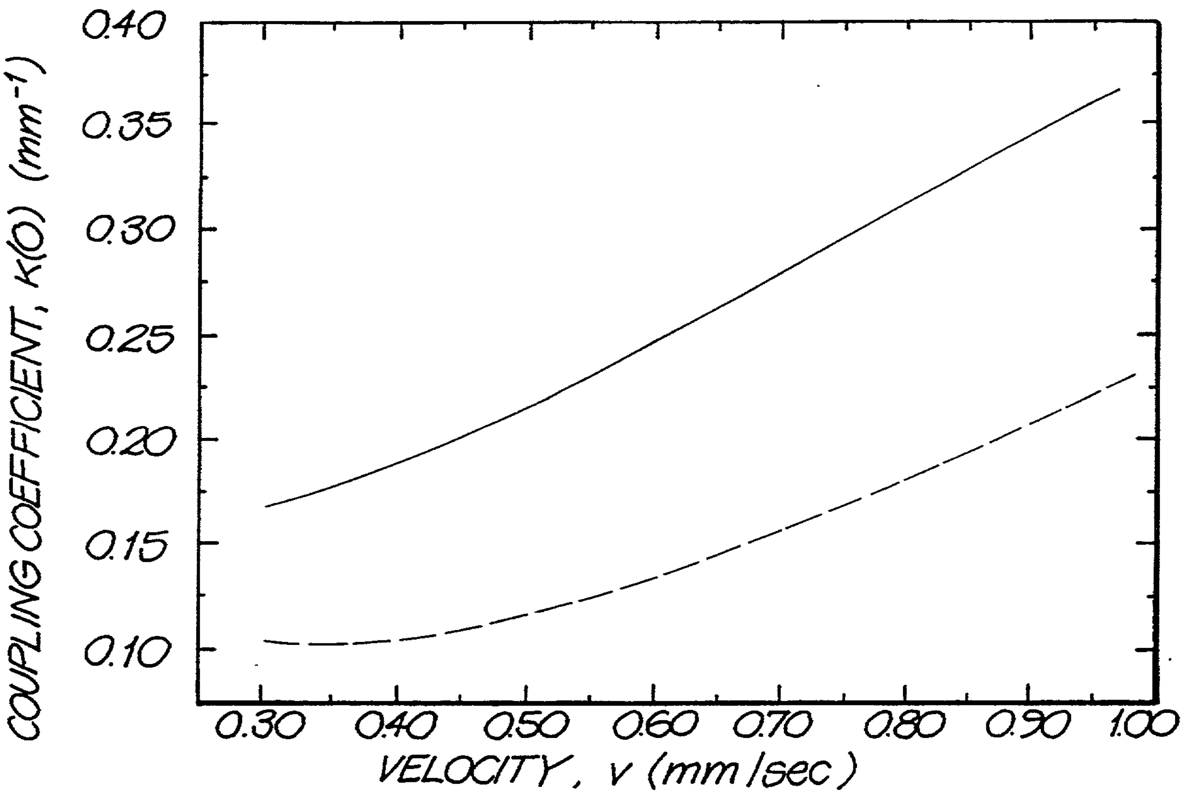

FIG. 6

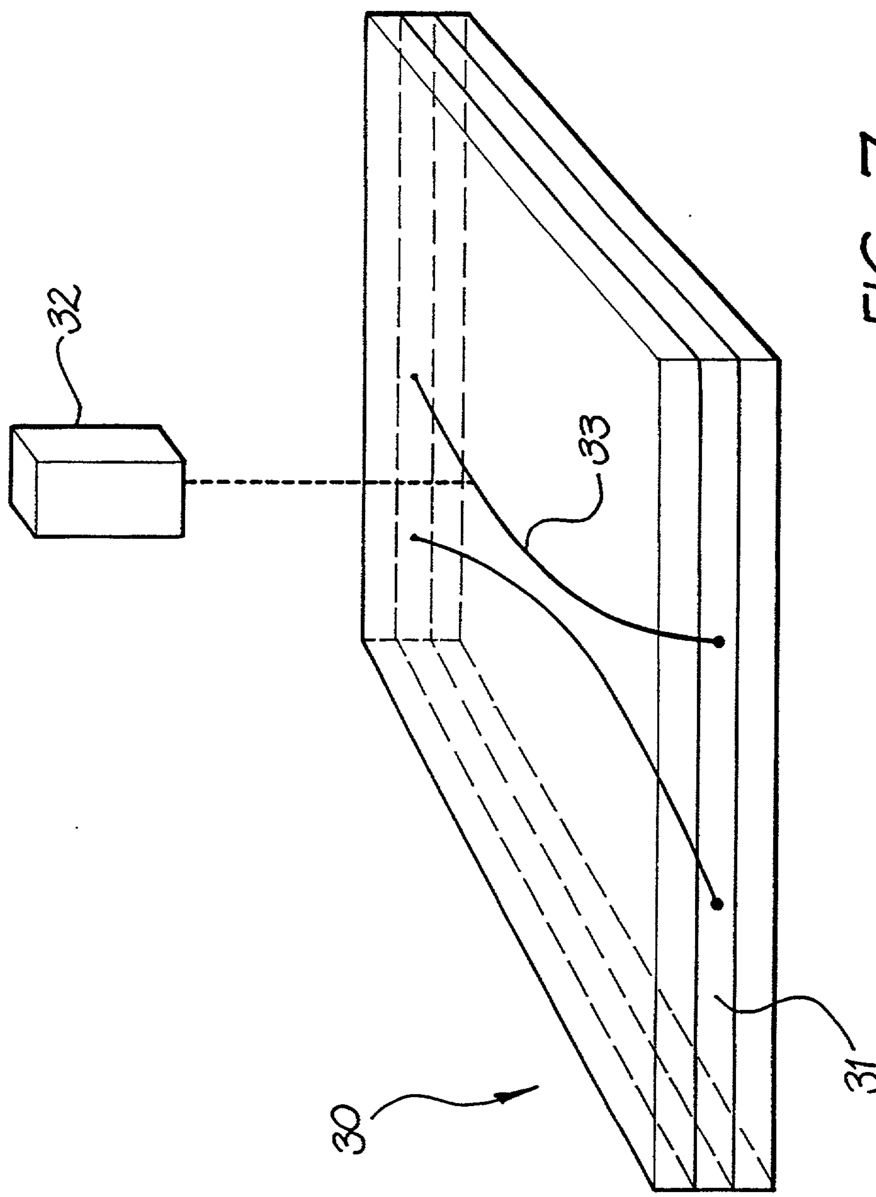

FIG. 7

DECLARATION FOR USA PATENT APPLICATION

(including Design and National Stage PCT) Attorney's Docket ID: ______________

As a below named inventor, I hereby declare that:
My residence, post office address and citizenship are as stated below adjacent to my name. I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought

on the invention entitled: METHOD OF FORMING AN OPTICAL WAVEGUIDE DEVICE
the specification of which:

____ is attached hereto.
(or)
_x_ was filed on 21 June 2000 as U S. Application No. or PCT International Application No. PCT/AU00/00698

and (if applicable) was amended on 7 September 2001
I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims. as amended by any amendment specifically referred to above. I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR 1 56

I hereby claim foreign priority benefits under 35 U.S.C. 119(a)-(d) or 365(b) of any foreign application(s) for patent or inventor's certificate, or 365(a) of any PCT International application which designated at least one country other than the United States of America, listed below and have also identified below, where priority is not claimed, any foreign application for patent or inventor's certificate, or any PCT International application, having a filing date before that of the application on which priority is claimed. (__ ADDITIONAL APPLICATIONS IDENTIFIED ON ATTACHED SHEET)

Prior Foreign Application No.	Country	Day/Month/Year Filed	Priority Not Claimed
PQ1110	AU	21/6/1999	

I hereby claim the benefit under 35 U.S.C 120 of any U.S application(s), or 365(c) of any PCT application designating the U S., listed below; and insofar as the subject matter of each claims of this application is not disclosed in the prior U.S. or PCT application in the manner provided by the first paragraph of 35 U.S.C. 112, I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR 1.56 which became available between the filing date of the prior application and the national or PCT filing date of this application. (__ ADDITIONAL APPLICATIONS IDENTIFIED ON ATTACHED SHEET.)

U.S. or PCT Parent Application No.	Parent Filing Date (Day/Month/Year)	Parent Patent No. (if applicable)

As a named inventor, I hereby appoint the registered practitioners of **LARSON & TAYLOR** associated with Customer Number 000881 to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith. Direct all correspondence to that Customer Number.

Direct all telephone calls to ______________________________,
at TEL (703) 739-4900 (Fax 703-739-9577) e-mail.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under 18 U.S.C. 1000 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon

1-00

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2-00

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SIGN AND DATE HERE Inventor's Signature		Date

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Residence - City, State/Country (if different from PO address)		
SIGN AND DATE HERE Inventor's Signature		Date